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Evidence of High Power HF Radiowave Self-Focusing in the Ionosphere: Preliminary Report of SURA-WIND Observations

P. RODRIGUEZ
M. KESKINEN

Charged Particle Physics Branch
Plasma Physics Division

YU. V. TOKAREV
V.A. ALIMOV
YU. I. BELOV
V.L. FROLOV
N.A. KARASHTIN
G.P. KOMRAKOV

Radiophysical Research Institute
Nizhny Novgorod, Russia

M.L. KAISER
M.D. DESCH

Goddard Space Flight Center
Greenbelt, Maryland

K. GOETZ

University of Minnesota
Minneapolis, Minnesota

J.-L. BOUGERET
R. MANNING

DESPA, OBSERVATOIRE DE PARIS
MEUDON, FRANCE

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P. Rodriguez, M. Keskinen,[1] Y. Tokarev, V. Alimov, Y. Belov, V. Frolov, N. Karashtin, G. Komrakov,[2] M. Kaiser, M. Desch[3], K. Goetz[4], J. Bougeret, R. Manning[5]

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[1]Naval Research Laboratory, Washington, DC
[2]Radiophysical Research Institute, Nizhny Novgorod, Russia
[3]Goddard Space Flight Center, Greenbelt, MD
[4]University of Minnesota, Minneapolis, MN
[5]DESPA, Observatoire de Paris, Meudon, France

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Experiments are currently being conducted using the Russian SURA ionospheric research facility in conjunction with the NASA/WIND satellite. One objective is to investigate the effects of interactions of high power, high frequency radiowaves with the earth's ionosphere. Recent experiments indicate that structured space plasmas along the propagation path impose a power law spectrum of intensity fluctuations on the transmitted waves, similar to scintillations. However, because the transmitted wave frequencies are near ionospheric plasma frequencies, other types of wave-plasma interactions may occur. One possible wave-plasma interaction is the self-focusing instability. In this brief report, we discuss preliminary results that suggest self-focusing was observed. The measurements can provide an important new diagnostic tool of high power radiowave interactions with the underdense ionosphere.

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1. Introduction

Most experiments with ionospheric high power transmitters such as the SURA facility (known generally as ionospheric "heaters") have relied on diagnostic measurements taken with ground-based instruments. Among the subjects of investigation at the SURA facility have been various high frequency (HF) wave-focusing effects of the ionosphere [Vas'kov and Gurevich, 1979; Erukhimov et al., 1997]. Recently, we have begun to acquire space-based measurements of wave-plasma interactions as a method of diagnosing these effects. Thus, we have shown [Rodriguez et al., 1998] that powerful HF transmitters can be used as probes of the space plasma near the earth from ionospheric to magnetospheric altitudes. A recent experiment conducted with the Russian SURA facility at about 9 MHz suggests that the self-focusing wave-plasma interaction was observed. In this report, we discuss one set of observations and present our preliminary conclusions based on comparison with model calculations.

2. Experiment Configuration

The SURA facility is located near the village of Vasil'sursk, about 40 km from Nizhny Novgorod, Russia. During a series of joint USA-Russian experiments involving the WAVES experiment onboard the WIND satellite, we have recorded the wave power transmitted from SURA on several days when WIND was within the beam of the transmitting array. The orbit of WIND allows experiments at a wide range of radial distances from the earth, from 10 R_e to 250 R_e, where R_e is in units of earth radii. For this experiment, WIND was at about 140 R_e upstream of the earth in the solar wind. The orbit of WIND is designed to maintain the satellite in the distant solar wind for many days as a monitor of solar-induced disturbances. As viewed from earth, the satellite can appear to rise and set with the sun for intervals of several days. This configuration allows the fixed SURA antenna pattern to sweep past the WIND satellite as the earth rotates. Thus, WAVES can sample the antenna pattern along approximately the east-west dimension. The SURA half-power beamwidth is approximately 6° in the east-west direction by about 20° in the north-south direction, so that the east-west radiation pattern can be transited in about 1 hour of earth rotation.

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The SURA radar array is composed of three sections, each section consisting of 48 crossed linear dipoles [Ilyasov and Belov, 1996]. The crossed dipoles can be combined to give either right or left circular polarization. Each section has dimensions of 100 x 300 meters, with overall array dimension 300 x 300 meters. The array beam can be electronically steered over a declination range of 12° to 85° in 3° steps by manual and/or automatic phasing of the dipoles. Power is generated in three 250-kW transmitters that are connected independently to the three array sections providing a total of 750 kW. For our experiment, the frequency of radiation was 8925 kHz.

The WAVES receiver was designed to observe solar radio bursts [Bougeret et al., 1995], but it also detects HF transmissions from the ground. The RAD2 portion of the WAVES receiver is a stepped frequency receiver covering 256 frequencies from 1.075 MHz to 13.825 MHz, in 50-kHz intervals, with 20-kHz bandwidth, and a detection threshold of ~7 nvolt/√Hz. The time interval for the receiver to step through 256 frequencies is 16.192 seconds, with the effective dwell time per frequency being about 60 ms. For our experiment, the stepping mode was changed to a continuous sampling of the 8.925-MHz channel only. The detection is done with a 15-meter-length dipole (S) in the spin plane of the satellite and an 11-meter-length dipole (Z) perpendicular to the spin plane. The S-antenna rotates with the spacecraft at a 3-sec period while the Z-antenna has no effective rotation because it is aligned with the spin axis. In order to avoid spin-induced modulation of the received SURA signal, the measurements that we discuss were made with the Z-antenna.

3. Experiment Measurement

In Figure 1, we show plots of the signal amplitudes received at WIND for the SURA transmissions between UT 1100-1150 on 18 June 1998. The local time at SURA was LT 1500-1550, and the overhead ionospheric critical frequency was about 6300 kHz, as determined with a local ionosonde. The wave power received has been converted to signal-to-noise ratios, based on the noise level of the WIND receiver, which is about 3.6×10^{-5} μvolts^2/Hz. The upper panel is a plot of SURA radiated power obtained in the 8925-kHz channel of the WAVES receiver. SURA was transmitting in continuous wave (CW) mode for the duration of the experiment, so the apparent signal fluctuations must be attributed to effects of propagation from the ground to the satellite. The distinctly spiky nature of the received signal is similar to previous observations [Rodriguez et al., 1998] made with the HAARP facility in Alaska in which it was concluded that wave interaction with ionospheric plasma density irregularities caused scintillation of the waves received at WIND. This effect is probably also present in the SURA measurements. However, the quasi-periodicity of the observed spikes and the greater power of the SURA experiment (750 kW versus 300 kW at HAARP) suggest that other, new effects may also be present. We suggest that the spiky structure is evidence for filamentation of the transmitted beam by a self-focusing plasma instability induced in the overhead ionosphere. In this scenario, the main SURA beam radiating into the overhead ionosphere at about 300-km altitude, emerges as a filamented beam at higher altitudes. The main beam then appears to be formed of many smaller "beamlets" that point

toward the WIND spacecraft. However, because WIND is a point of infinitesimally small angular size, only those beamlets that actually illuminate the spacecraft are recorded as the earth rotates. The low-level intervals of the data correspond to the times when no beamlet was shining on WIND, even though the satellite was still within the main beam of SURA. The quasi-periodicity of the spikes also suggests that the filamentation may have occurred at some preferred scale size.

In the lower panel of Figure 1, we have calculated running averages of the data in the upper panel in order to smooth out the spiky nature and to allow a comparison with the calculated antenna pattern of SURA. The average is calculated over 5120 points (about 5.4 min) and then stepped forward by 1024 points (about 1 min). This running average removes the spiky variations, although some fluctuations remain. The remaining fluctuations are real and indicate larger scale variations of the received power that may be associated with large-scale ionospheric irregularities, perhaps gravity waves, etc. However, a comparison with the calculated antenna pattern shows relatively good correspondence. Thus, we are assured that the WIND measurements scanned the main SURA beam.

4. Threshold for Self-Focusing

The threshold wave power density I_t for the underdense thermal self-focusing instability can be written [Perkins and Goldman, 1981] as

$$I_t = (1.5 \times 10^{-6}\ \mathrm{W\ m^{-2}})(10^{6}\ \mathrm{cm^{-3}}/N_e)^3(T_e/1000°\mathrm{K})^4(f/15\ \mathrm{MHz})^3\ \xi,$$

where N_e is the ambient ionospheric electron density in $\mathrm{cm^{-3}}$, T_e is the ambient electron temperature, f is the wave frequency in units of MHz, and ξ is a factor of order unity. We take $N_e \sim 5 \times 10^5\ \mathrm{cm^{-3}}$, $T_e \sim 1000°\mathrm{K}$, and f=8.9 MHz and find that $I_t \sim 0.2 \times 10^{-5}\ \mathrm{W\ m^{-2}}$. We may also estimate the power density radiated into the ionosphere by SURA at about 750 kW into the main beam (angular cross-sectional area $A=\pi ab$, where $a=6°$ and $b=20°$) at 300 km altitude. Corrections for various losses such as absorption, E-layer defocusing, and wave scattering give an estimated reduction of total power by 4 dB. The resulting power density is then about 3×10^{-5} W $\mathrm{m^{-2}}$. This is greater than the threshold I_t, and thus we conclude that the underdense thermal self-focusing instability could have been excited.

Typically, individual spikes are detected by WIND with about 3- to 4-sec time widths; assuming that the spikes correspond to quasi-stationary beamlets, we can estimate the cross-track dimensions using the earth's rotation rate. With WIND at a radial distance of 138.9 R_e, the east-west dimension of a typical beamlet is about 300 km at the position of WIND. If we map this dimension down to an altitude of the ionosphere over SURA, i.e., about 300 km, the typical east-west dimension is about 100 meters. Ionospheric structures on the order of 100 meters were also observed in the presence of high power HF heating [Basu et al., 1997] and were attributed to

thermal self-focusing. Recently, simulations of the thermal self-focusing instability for ionospheric applications [Guzdar et al., 1998] clearly show beam filamentation phenomena.

5. Summary and Conclusions

The SURA-WIND experiment discussed in this report is one of a series of experiments utilizing high power HF transmitters on the ground in conjunction with space-based receivers. These experiments are demonstrating that the combined ground-based and space-based facilities can provide an important new approach to the study of space plasmas and the effects of intense wave-plasma interactions. Because the transmitted frequency is above, but close to, the maximum plasma frequency of the ionized medium, significant wave-plasma interactions may occur. Thus, the measurements show effects that can arise from both natural and induced plasma structures. The observations of Figure 1 are not unique; other experiments in the same series have shown similar effects. In this report, we present evidence that a self-focusing instability has been observed, which had the effect of filamenting the SURA beam into smaller beamlets. This preliminary conclusion requires further investigation and analysis. In particular, as the self-focusing interactions requires power levels above some threshold, we plan to conduct new experiments at various power levels.

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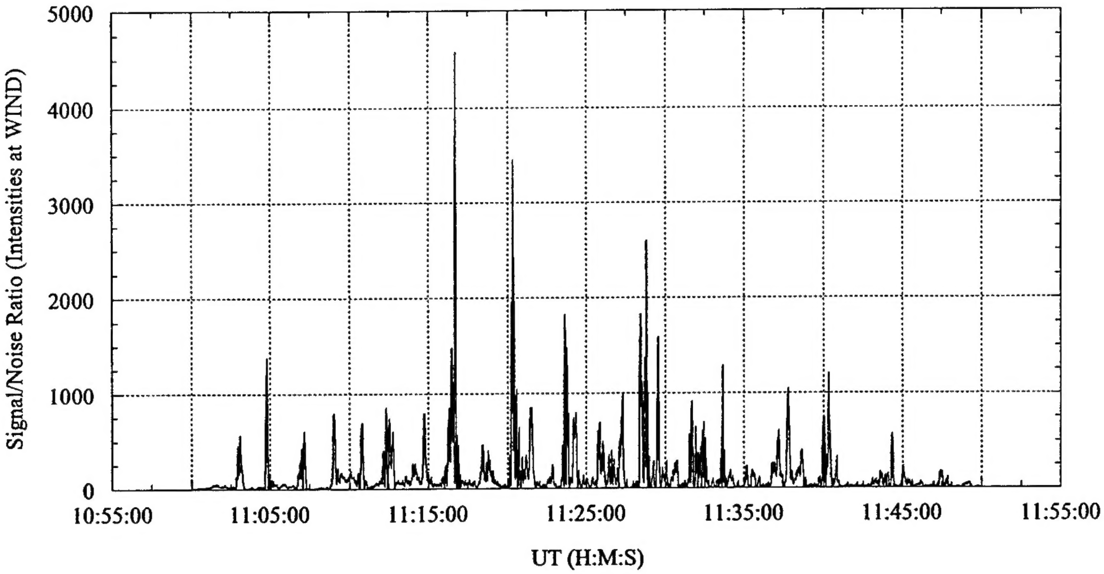
Figure Caption

Figure 1. Measurements of the SURA radiated power at 8925 kHz, as observed by the WIND spacecraft. The upper panel shows data taken by the WAVES receiver during transit of the SURA antenna pattern. The intense spikes may be evidence of filamented beam structure. The lower panel is a running average of the data and provides a direct comparison with the calculated SURA antenna pattern.

Evidence of Self-Focusing Filamentation

SURA-WIND 18 June 1998
Transit of Antenna Pattern
Total Power 750 kW / 8925 kHz



SURA Antenna Pattern at 8925 kHz
(± 8° about maximum)
Measured at WIND 18 June 1998

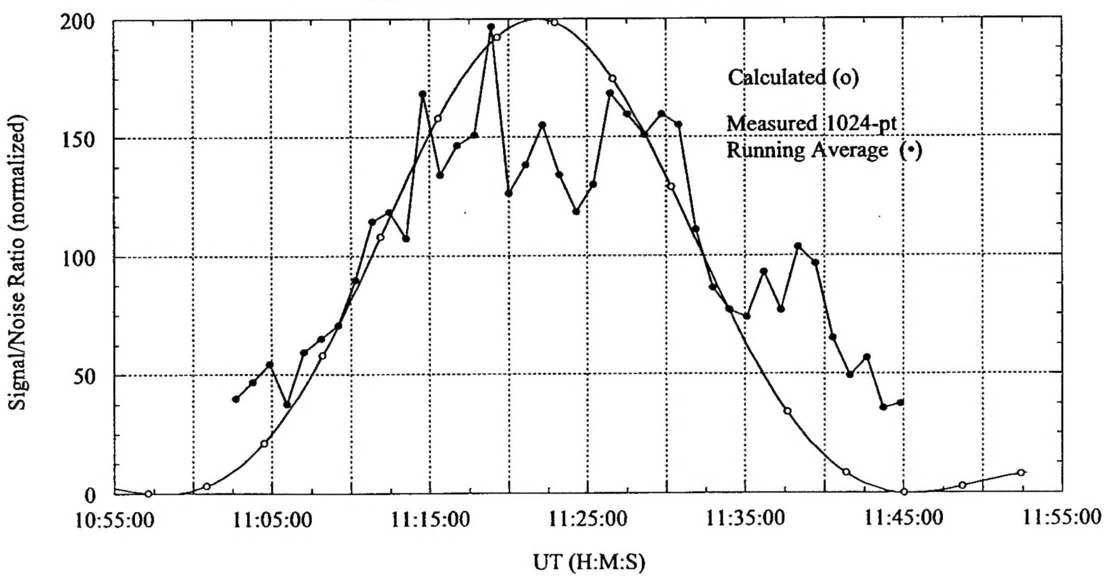


Figure 1